Hypersonic Flow Physics Program

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Flow Physics and Test Media Effects

- Motivations for this work
  - Achieve a better physical understanding of high-speed reacting flows for propulsion applications
  - Define the effects of vitiates in facility testing of engine flowpaths and allow extrapolation to flight conditions
- Both areas of research require the same "tools"
  - Well designed experiments and resulting databases
  - High fidelity non-intrusive diagnostics
  - Accurate simulation tools

Test Media Effects

- Hypersonic propulsion devices are developed in ground test facilities that produce vitiates
- Vitiate effects on engines are not well enough known to accurately predict flight performance of the combustor
- Need method that compensates for vitiates to accurately predict engine flame holding in flight, based on ground testing in vitiated air

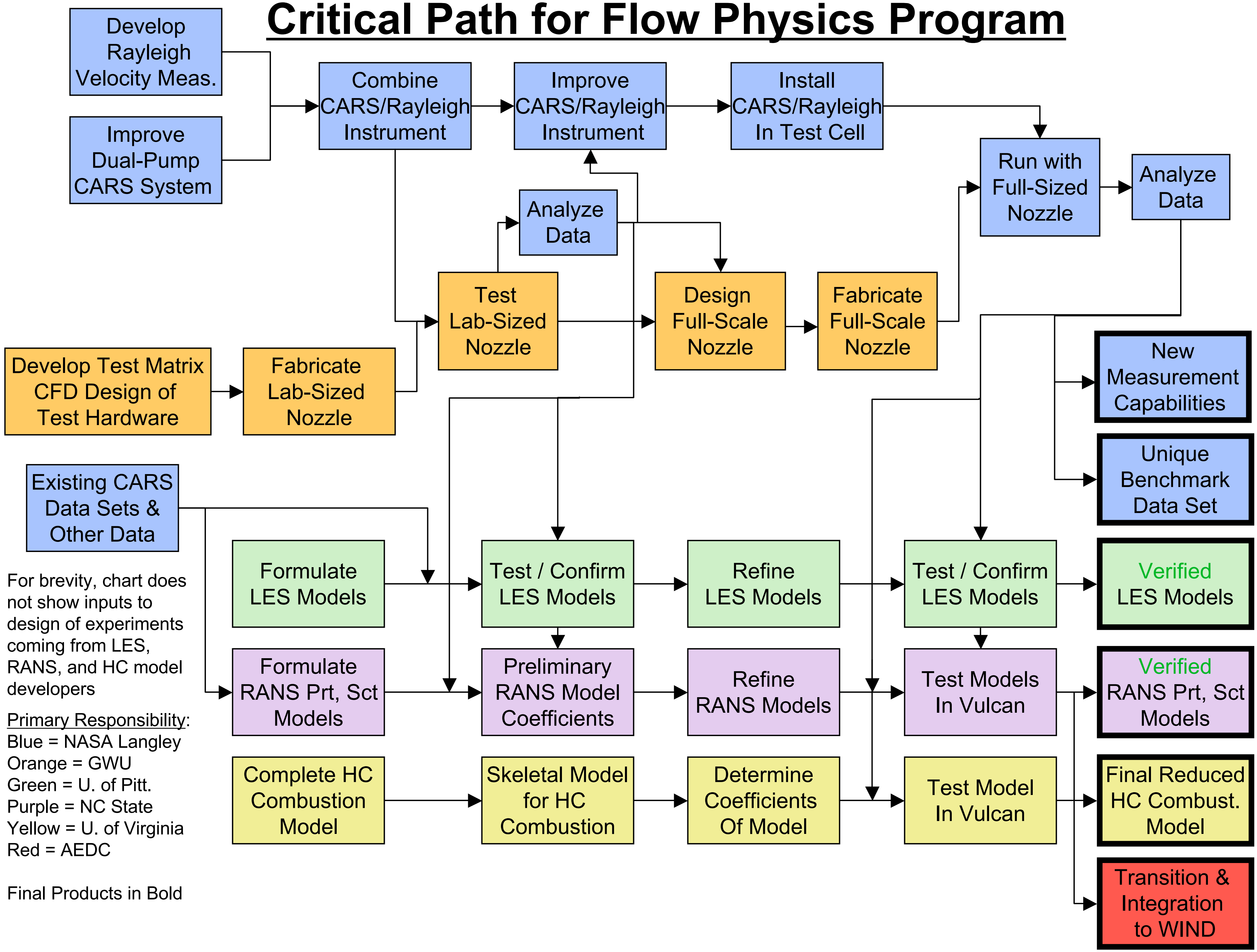
Analysis Requirements

- Develop enhanced codes to perform predictions based on an increased capability to model turbulence, turbulent mixing, and kinetics
- Develop new kinetics models
  - Reduce the complexity of the chemistry by up to a factor of 100
  - Identify and verify primary chemical interactions through sensitivity studies and experimentation
- Improve diagnostic capabilities for measuring mean and fluctuating temperature, velocity, and chemical species
  - Increase precision of the existing temperature and species measurements and add a 3-component velocity measurement capability, to fully characterize a supersonic combusting flows for the first time

Overall Project Scope

- Conduct experiments using simplified geometry and collect critical data for modeling improvements
- Increase diagnostic capability to collect mean and fluctuating data (velocity, temperature, and species)
- Improve fidelity of simulation tools (VULCAN and WIND codes) with improved phenomenological models
  - Turbulence
  - Chemical Kinetics
  - Interactions between these phenomena
- Support the development of advanced simulation tools including large eddy simulation and hybrid RANS-LES capabilities for component and flowpath design

Critical Path for Flow Physics Program



For brevity, chart does not show inputs to design of experiments coming from LES, RANS, and HC model developers

Primary Responsibility:
Blue = NASA Langley
Orange = GWU
Green = U. of Pitt.
Purple = NC State
Yellow = U. of Virginia
Red = AEDC

Final Products in Bold

Experiments

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George Washington University

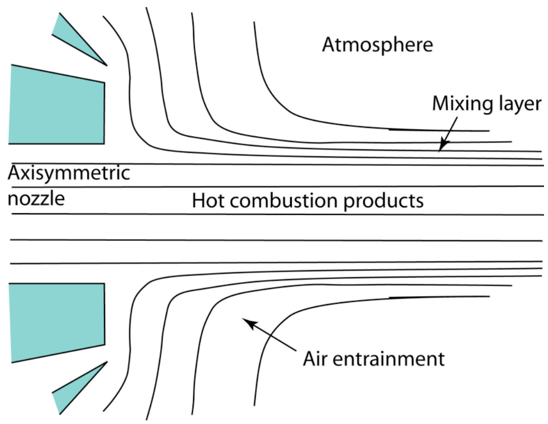
Diego Capriotti and Tom Mills
NASA Langley Research Center

NRA - Supersonic Combustion Free-Jet Experiment

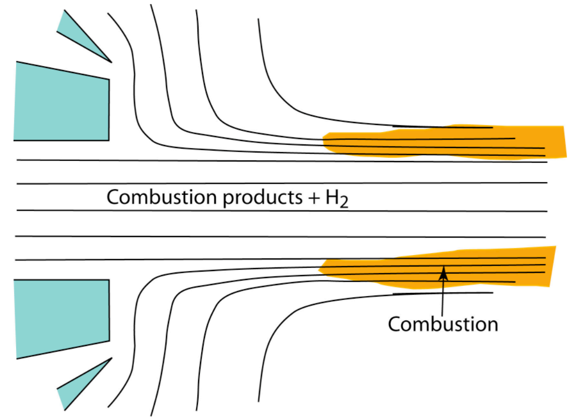
- Objective to provide experimental database for development of turbulence and chemistry models employed in CFD codes for hypersonic airbreathing engines
  - Detailed flow field data
  - Mean and turbulence statistics
  - Multiple simultaneously measured parameters (*u*, *v*, *w*, *T*, composition)
- Axisymmetric coflowing freejet geometry
  - High-speed (*M*=1, 1.6, 2) centerjet of combustion products (contains excess O_2 or excess H_2)
  - M≤1 coflow of unheated gas (air, H_2, CH_4, etc.)
  - Multiple possible cases, attached and detached flames, mixing only
- Many advantages
  - Good optical access, long run times
  - Symmetry allows fewer spatial points
  - More repeat measurements at each point for better statistics

Supersonic Combustion Free Jet Experimental Configurations

Case 1: Mixing

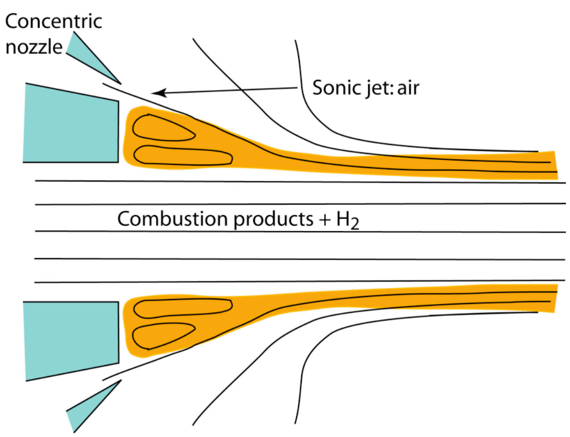


Case 2: Combustion

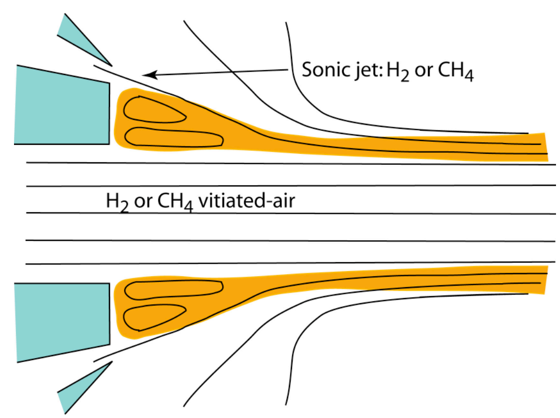


Case 3: Combustion with Flameholding:

(a) Center-jet fuel

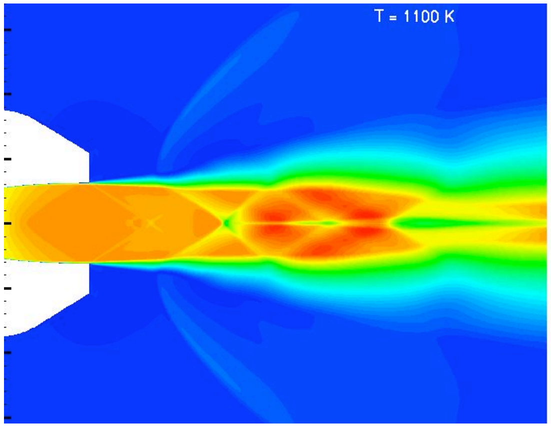


(b) Coflow fuel

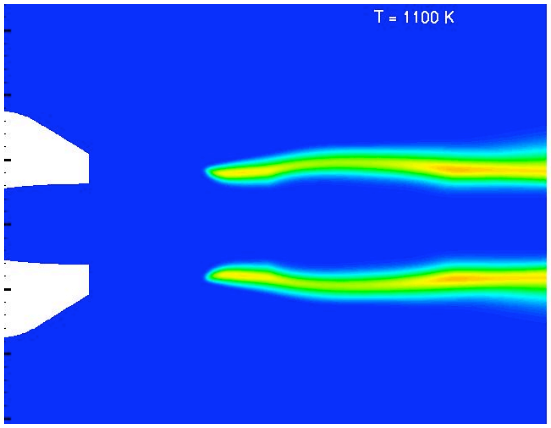


Conditions With and Without Flameholding Verified by CFD

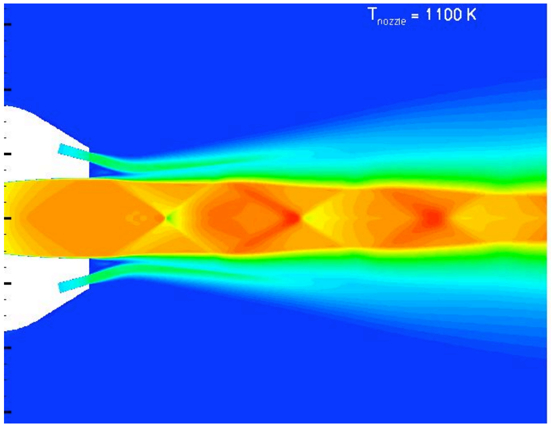
Case 2: Mach Number Contours



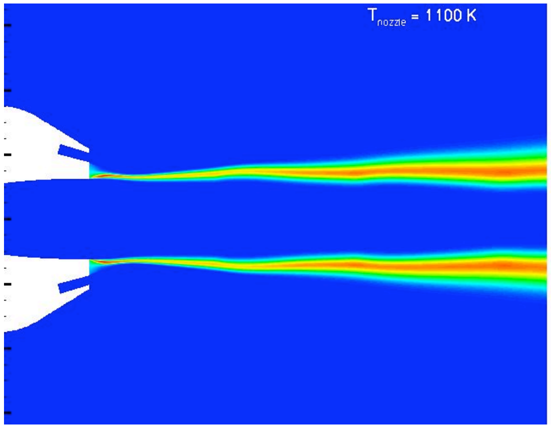
Case 2: OH Concentration Contours



Case 3: Mach Number Contours



Case 3: OH Concentration Contours

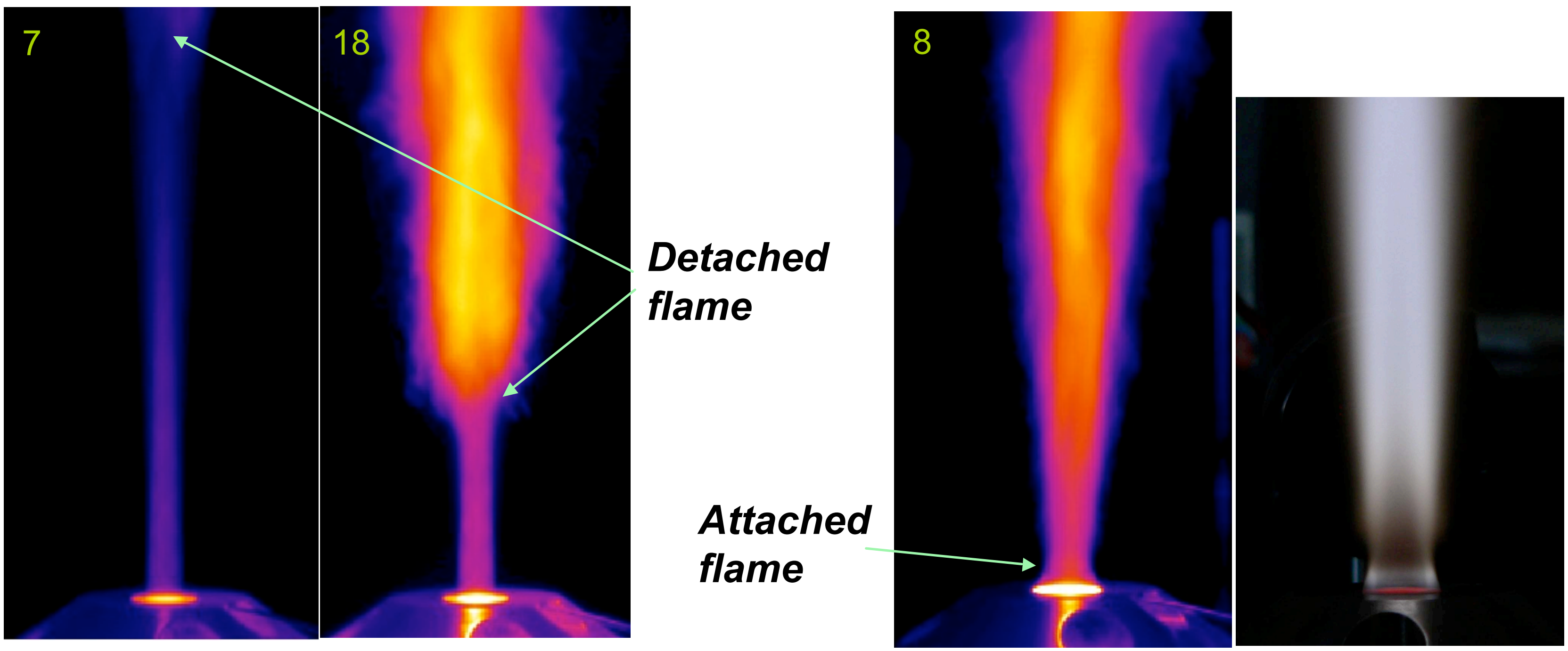


Flameholding Visualizations

- **Selected Examples From Test Matrix**
  - Cases with attached and detached flames
  - H_2 rich center jet with air coflow and vitiated air center jet with H_2 (or CH_4) coflow
  - M=1 and M=2 center jet

M=2 Vitiated Air Center Jet with Subsonic H_2 Coflow (ϕ=1)

M=1 "Vitiated" H_2 Center Jet (50% H_2, T_{exit}~1700 K) with Sonic Air Coflow

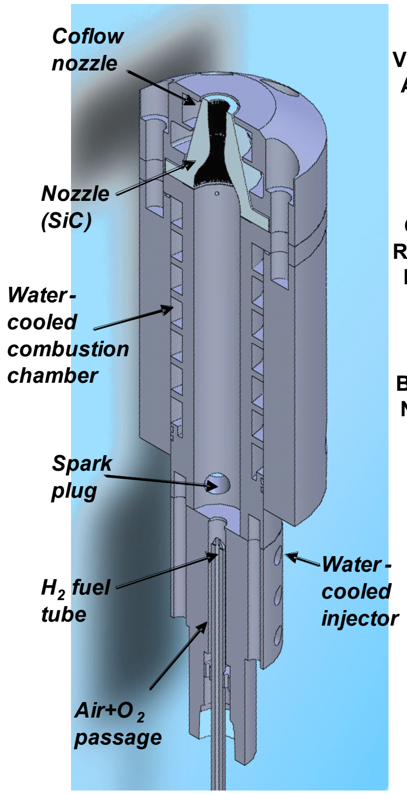


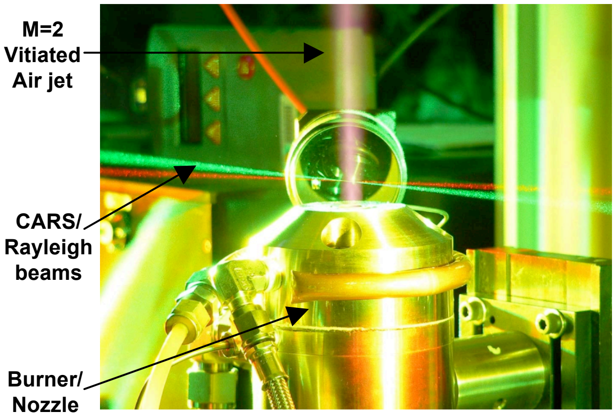
T_{exit}~935 K ***T_{exit}~1185 K***

IR (~8μm) ***Visible (true color)***

Laboratory and Full-Scale Models

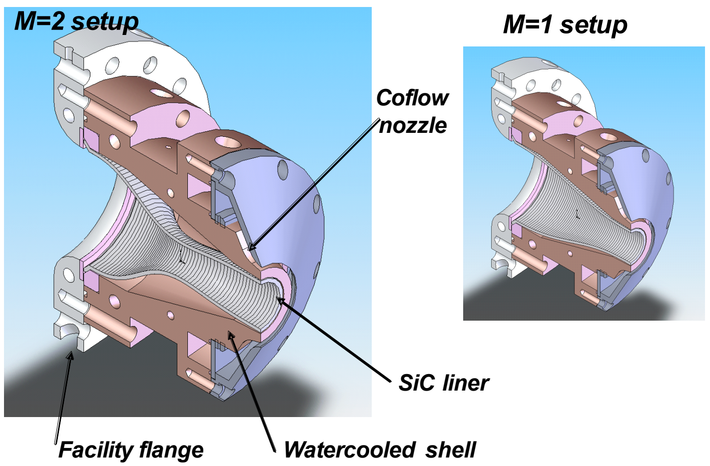
Small-scale facility





- **Operates in laser laboratory**
- **10 mm diameter Center jet**
- **Validate optical techniques**
- **Validate test matrix**

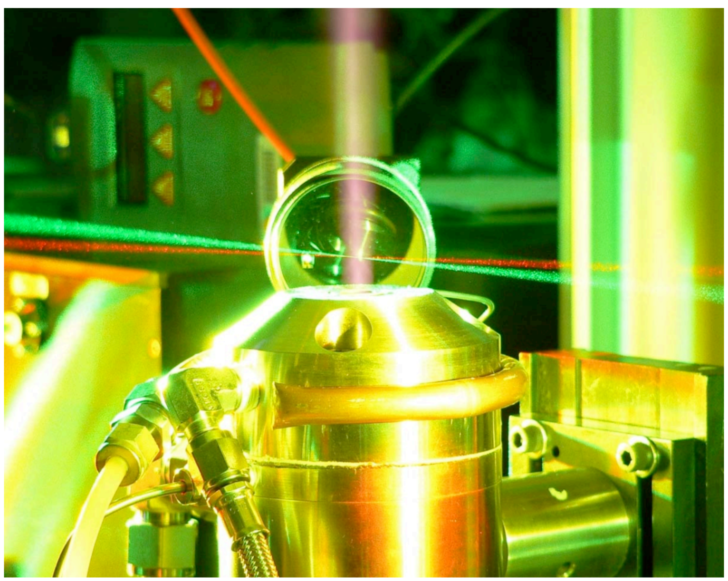
Large-scale facility (nozzle shown only)



- **Nozzle connects to LaRC DCSCTF vitiated air heater**
- **63.5 mm dia. centerjet**
- **Final database**
- **Diagnostics better spatially resolve flow turbulence**

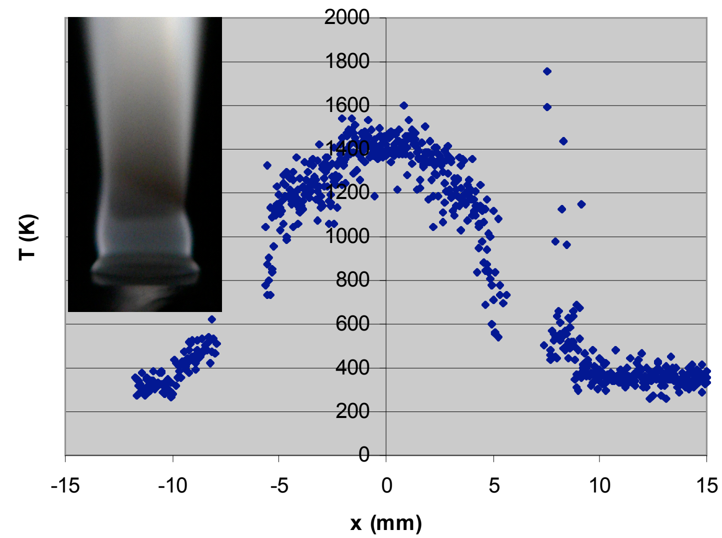
Laboratory Experiments

- Acquired CARS-IRS measurements in laboratory supersonic combusting jet hardware
  - Objective to shake down CARS-IRS technique
- Published results at AIAA Conferences



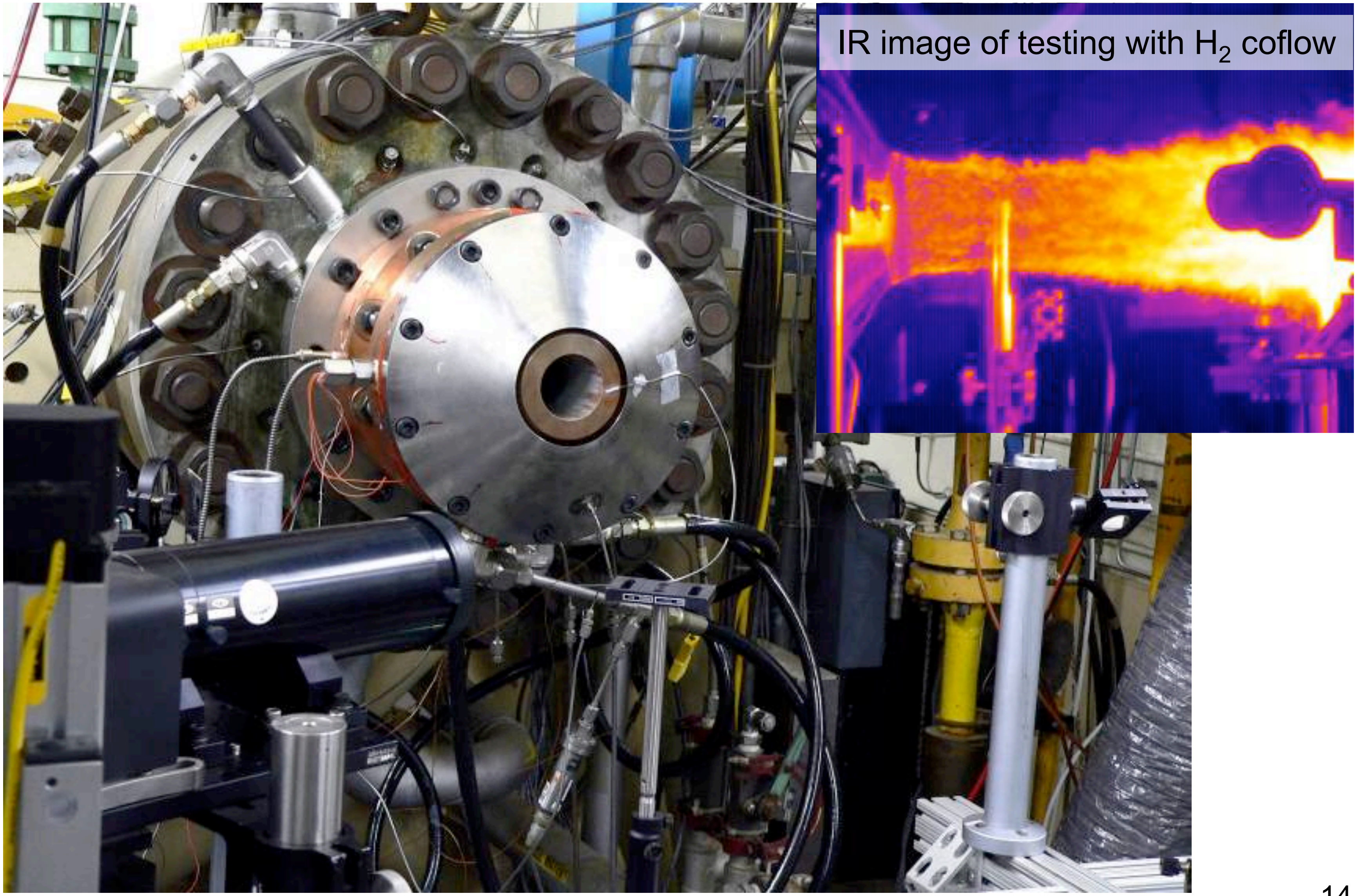
Burner in operation

H_2 coflow



Temperature survey at nozzle exit

Model Testing in DCSCTF



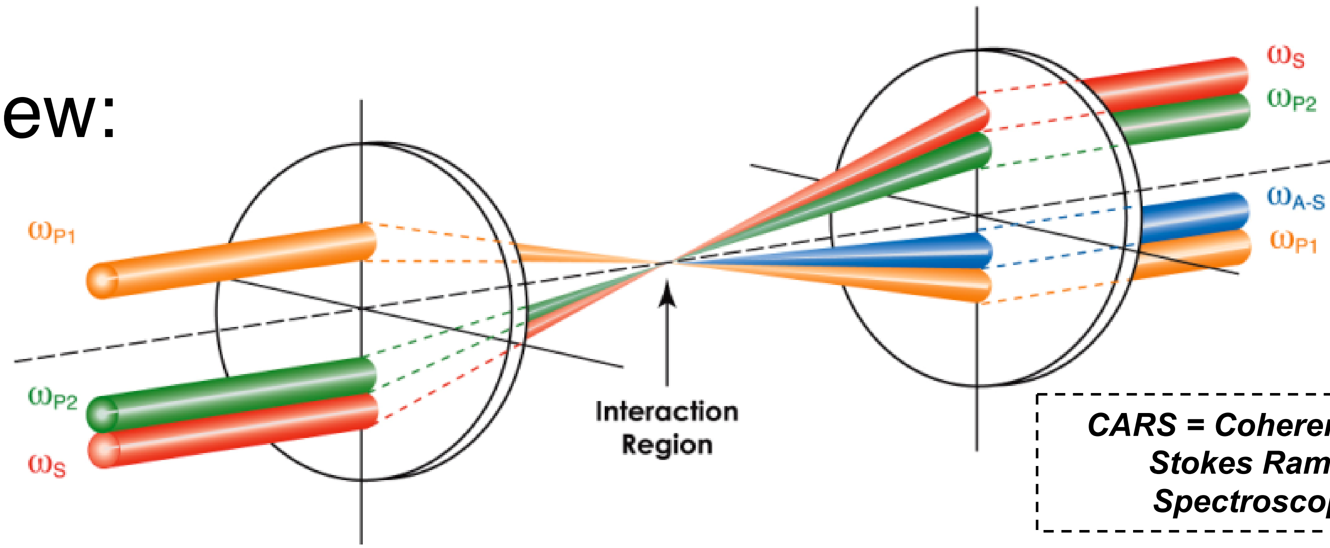
IR image of testing with H_2 coflow

Diagnostics

Paul Danehy
NASA Langley Research Center

Diagnostics: CARS / Rayleigh

Overview:

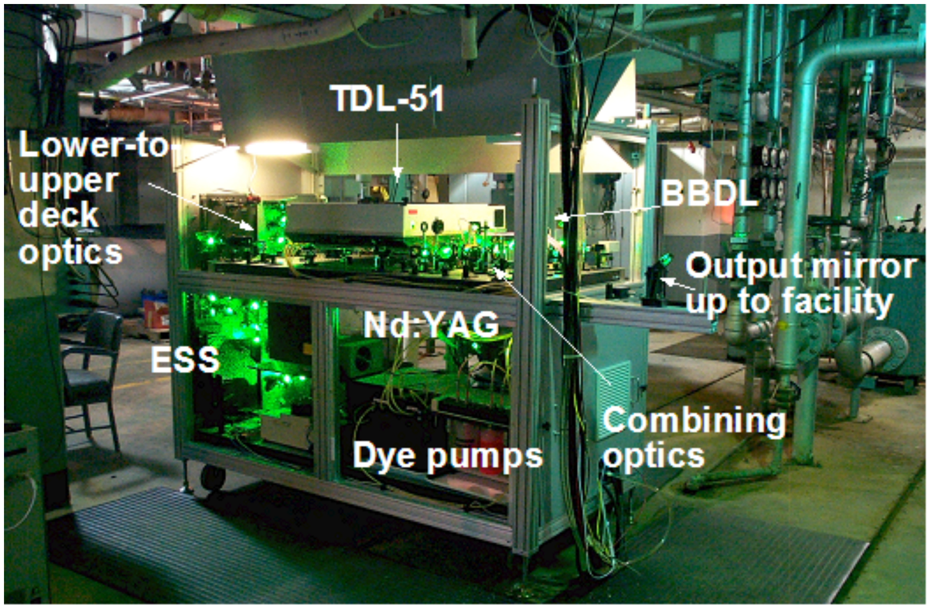


CARS = Coherent anti-Stokes Raman Spectroscopy

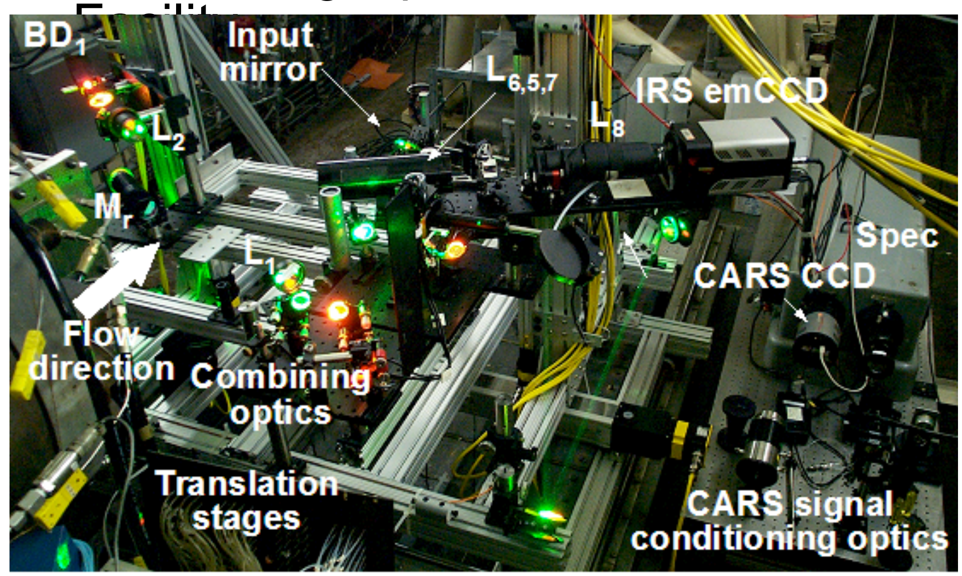
- <u>CARS</u>: 3 incoming beams generate a blue beam
  - Blue beam carries information about temperature and composition
  - Can probe N_2, O_2, H_2, H_2O, CO_2, NO, and others.
- Captured Rayleigh scattering from the green beam
  - Captured from 3 angles: measure 3 components of velocity
  - Determined density from magnitude of scattering
- Marriage of CARS & Rayleigh is unique
  - Is the most thorough characterization of reacting gas state ever

CARS System Installation

Transmitting Station



Receiving Optics Station in Facility



- Mobile CARS/IRS System built and tested in laboratory
- Transmitting Station has been installed in basement under DCSCTF
  - 3 lasers passed through hole in ceiling to facility.
- Beams are collected by X-Y-Z traverse stages:
  - forms CARS focus and holds Rayleigh collection optics.
- Shakedown in June/July; Testing began Aug.

Diagnostics Summary

- CARS & Rayleigh successfully combined
  - Simultaneous measurements of *T, V, species* in an atmospheric pressure flame
- Built Mobile CARS/Rayleigh System
  - Installed and used in facility for testing large scale jet flame
- Testing anticipated to conclude in December
  - Preliminary results 6 months after completion of test
    - Hand off to other program participants March 08
  - Final results 9 months after completion of test

Large Eddy Simulation

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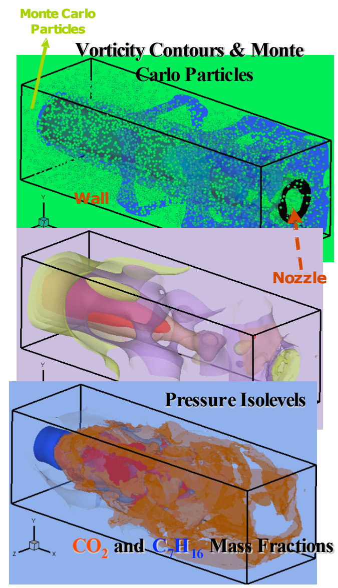
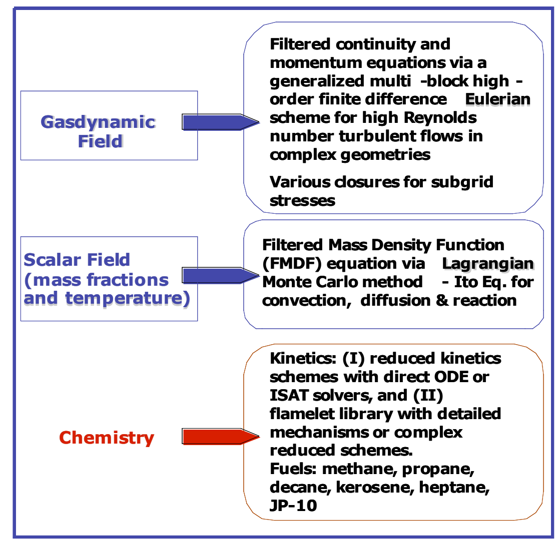
NRA - Large Eddy Simulation

Objectives

- Develop a validated high-fidelity numerical model for high speed turbulent reacting flows.
- Study combustors of interest to NASA for various flow/combustion parameters via numerical models.
- Improve basic understanding of turbulent combustion in supersonic and hypersonic flows.





NRA - Large Eddy Simulation

FY 2007/08 Key Milestones

- Development and implementation of high-order finite-difference compact operators and WENO schemes for flows with shock waves.
- Extension of scalar FMDF and existent LES submodels to compressible flows.
- Simulations of compressible subsonic turbulent flows in realistic systems via new numerical methods and subgrid models.
- Development of a stochastic formulation for compressible velocity-scalar FMDF.

RANS and Hybrid RANS Code Development

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Jay Edwards

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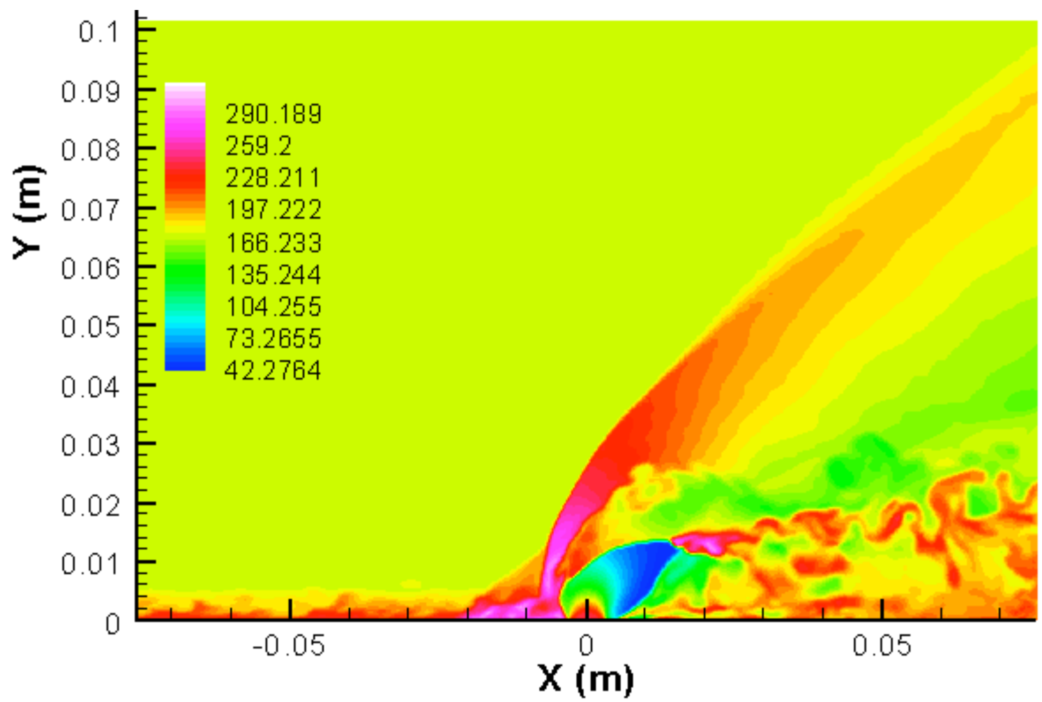
NRA - RANS and Hybrid RANS Code Development

Objectives

- Development and refinement of hybrid large-eddy / Reynolds-averaged simulation (LES/RANS) methods for high-speed turbulent flows
- Applications to sonic injection into a supersonic crossflow, crossing-shock interactions, and shock-train propagation
- Implementation of LES/RANS methods into NASA's VULCAN code
- Development of automatic block-splitting / partitioning algorithms for structured meshes and implementation into VULCAN (subcontract to Corvid Technologies)



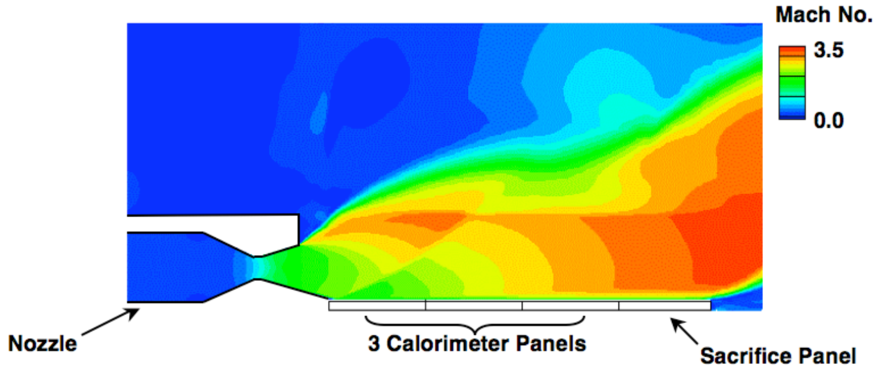
NRA - RANS and Hybrid RANS Code Development

FY 2007/08 Key Milestones

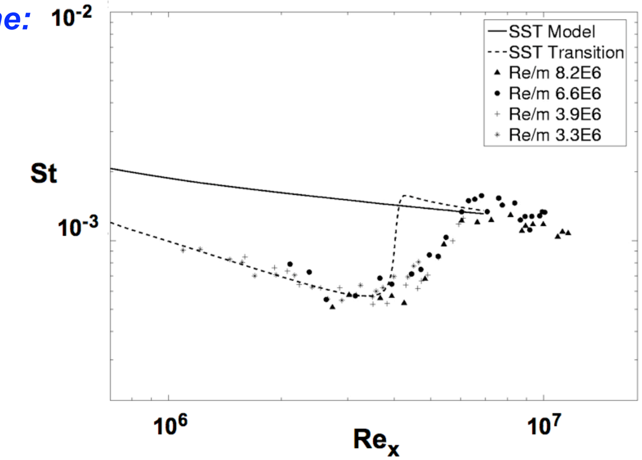
- Improved RANS-to-LES blending functions and methods for controlling turbulence energy distribution developed and demonstrated
- LES/RANS simulations of air-air sonic injection experiments of Gruber, et al (AFRL) completed; helium-air simulations to be performed next
- Analysis of LES/RANS data to calculate turbulent Schmidt /Prandtl number variation underway
- Generalized recycling / rescaling module for structured meshes written and being debugged and tested
- Beta version of block-splitting / merging codes developed and delivered to NASA

Simulation Using the Wind-US Flow Solver at NASA/GRC

Wind-US/Conjugate Heat Transfer Applied to Rocket with Cooled Panels:



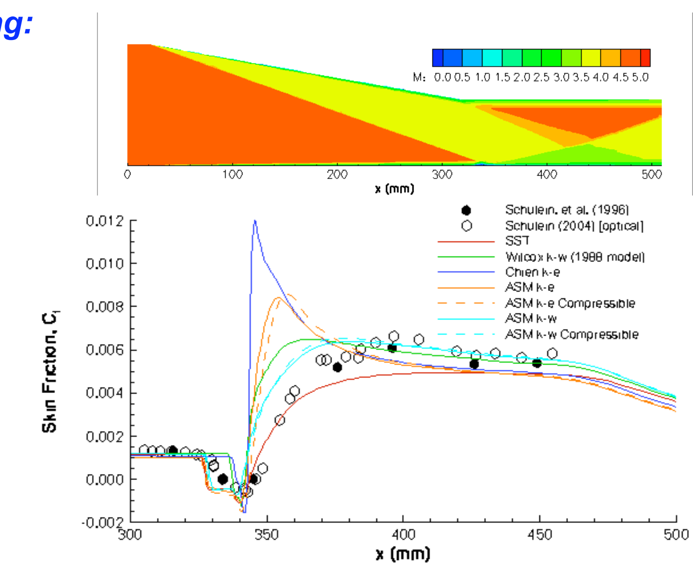
Boundary Layer Transition for Mach 7.9 Cone:



FY08 Plans:

1. Add advanced turbulence models (EASM's) and variable Pr_t, Sc_t capability; coordinate with Vulcan CFD R&D.
2. Implement and validate multiphase kinetics capabilities.
3. Examine UVA mode-transition experimental configuration; address vitiated air effects.

Advanced EASM turbulence modeling:



Combustion Kinetics

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University of Virginia

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NRA - Chemical Kinetics Modeling

- Ignition delay and flame strength and the resultant flame holding can be improved or weakened by facility contaminants altering the performance of engines as compared to flight in the atmosphere
- Accurate finite-rate chemical kinetic models are required to understand the effects of contaminants in facilities and to extrapolate results from ground-based facilities to flight
- Systematically developed *Reduced Reaction Models Approach* allow the large chemical kinetic models reduced to a tractable level without losing significant accuracy
- Have developed number of tools to automate the implementation of above concepts to any detailed reaction model selected. These include:
    - Reaction pathway analyses/fast reactions
    - Steady-state species selection based on pre-determined tolerance level and choice of obtaining explicit/implicit expressions for species in SS
    - Have developed 15-18 step reduced reaction models for ignition and propagation of ethylene/methane/hydrogen/air mixtures

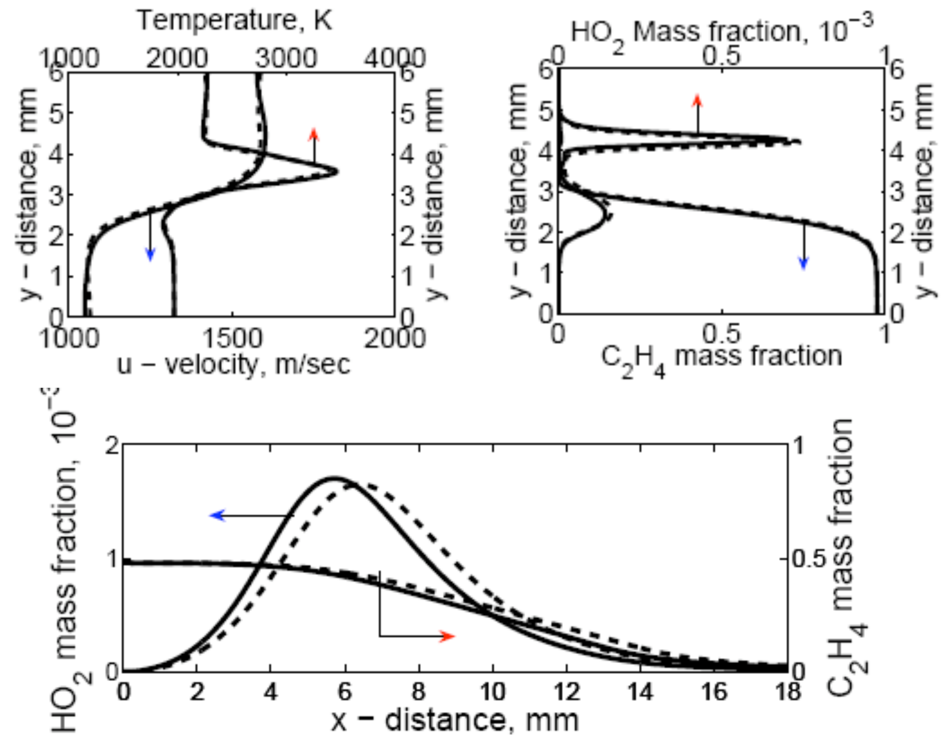
NRA - Chemical Kinetics Modeling

•Reduced models developed have been implemented in multidimensional, laminar reacting flow simulations using SPARK 2D code [see figs: detailed (solid), 18-step (dashed)].

•Relative ***computational time*** (see C&F paper for details) :

Detailed/Skeletal/18-step
RRM=1.0/0.364/0.115

(only chemical source terms –do not include savings on solving pde's)



Summary:

• Have developed series of reduced reaction models for H2-air (4-steps), CH4-air (13 steps), and C2H4-air (15-18 steps) that are valid for a wide range of equivalence ratios, pressures, and temperatures.

•Models have been readily exported to multi-dimensional computational flow codes.

Future Work:

• Need to couple with turbulence models

Concluding Remarks

- FY07 tasks are on schedule
  - Earlier delays due to nozzle fabrication and final diagnostic development in combustion experiment have been overcome
- Diagnostic and experimental activities completed in laboratory facilities
- Testing in full scale facility (DCSCTF) began in July 2007 following completion of nozzle fabrication
- Work to further enhance the CARS-Rayleigh System is currently underway
- Work under NRA's have been successful and on schedule
- Work represents a comprehensive investigation and tool development activity for a very complex combustion environment